

OECD/SERENA Project Report

Summary and Conclusions

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NEA/CSNI/R(2014)15

Organisation de Coopération et de Développement Économiques
Organisation for Economic Co-operation and Development

English text only

**NUCLEAR ENERGY AGENCY
COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS**

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Summary and Conclusions

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THE COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

“The Committee on the Safety of Nuclear Installations (CSNI) shall be responsible for the activities of the Agency that support maintaining and advancing the scientific and technical knowledge base of the safety of nuclear installations, with the aim of implementing the NEA Strategic Plan for 2011-2016 and the Joint CSNI/CNRA Strategic Plan and Mandates for 2011-2016 in its field of competence.

The Committee shall constitute a forum for the exchange of technical information and for collaboration between organisations, which can contribute, from their respective backgrounds in research, development and engineering, to its activities. It shall have regard to the exchange of information between member countries and safety R&D programmes of various sizes in order to keep all member countries involved in and abreast of developments in technical safety matters.

The Committee shall review the state of knowledge on important topics of nuclear safety science and techniques and of safety assessments, and ensure that operating experience is appropriately accounted for in its activities. It shall initiate and conduct programmes identified by these reviews and assessments in order to overcome discrepancies, develop improvements and reach consensus on technical issues of common interest. It shall promote the co-ordination of work in different member countries that serve to maintain and enhance competence in nuclear safety matters, including the establishment of joint undertakings, and shall assist in the feedback of the results to participating organisations. The Committee shall ensure that valuable end-products of the technical reviews and analyses are produced and available to members in a timely manner.

The Committee shall focus primarily on the safety aspects of existing power reactors, other nuclear installations and the construction of new power reactors; it shall also consider the safety implications of scientific and technical developments of future reactor designs.

The Committee shall organise its own activities. Furthermore, it shall examine any other matters referred to it by the Steering Committee. It may sponsor specialist meetings and technical working groups to further its objectives. In implementing its programme the Committee shall establish co-operative mechanisms with the Committee on Nuclear Regulatory Activities in order to work with that Committee on matters of common interest, avoiding unnecessary duplications.

The Committee shall also co-operate with the Committee on Radiation Protection and Public Health, the Radioactive Waste Management Committee, the Committee for Technical and Economic Studies on Nuclear Energy Development and the Fuel Cycle and the Nuclear Science Committee on matters of common interest.”

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EXECUTIVE SUMMARY

The OECD/SERENA Project Integration Report summarises the outcome of a broad range of activities conducted in the framework of the Organisation for Economic Cooperation and Development (OECD) Steam Explosion Resolution for Nuclear Applications Project (OECD/SERENA) to address remaining issues on fuel-coolant interaction (FCI) mechanisms and their effect on ex-vessel steam explosion energetics. The scope the OECD/SERENA project was to resolve uncertainties in the remaining issues and to bring the code capabilities to an adequate level for use in reactor safety applications. This scope was accomplished with the completion of three major tasks: (1) an experimental programme consisting of two sets of steam explosion experiments in two different facilities; (2) an analytical programme consisting of pre-test calculations in support of test specifications and post-test calculations in support of data analysis and code assessment, and also a code benchmark exercise; and (3) a reactor calculation exercise repeating the one performed in the framework of the CSNI/WGAMA SERENA activity performed from 2001 to 2006 (also referred to as SERENA Phase I, published as CSNI/R(2007)/11).

The objectives of the experimental programme were to provide data: (1) to clarify the explosion behaviour of prototypic corium melts and for validation of steam explosion models for prototypic materials; and (2) for steam explosion behaviour in two different geometries to verify the geometrical extrapolation capabilities of the codes. These objectives were to be accomplished by conducting complementary sets of six experiments each at two different facilities: KROTOS at the *Commissariat l'Énergie Atomique et aux Énergies Alternatives* (CEA) in Cadarache, France, representing one-dimensional FCI configuration involving nominally 5 kilograms of prototypic corium melt, and TROI at Korea Atomic Energy Research Institute (KAERI) in Daejeon, Korea, representing multi-dimensional FCI configuration involving nominally 20 kilograms of prototypic melt.

Important observations from KROTOS and TROI experiments in the framework of the OECD/SERENA project are:

- Prototypic corium melt (i.e., predominantly a mixture of UO_2 and ZrO_2) does not produce stronger explosion energetics relative to simulant melt compositions (e.g., KROTOS alumina tests) even though the calculated energetics in some TROI and KROTOS tests in the current series were higher than in previous experiments with prototypic mixtures.
- Eutectic melt compositions were found to have no higher propensity to steam explosion compared to non-eutectic compositions, as previously noted based on past experiments.
- The TROI test with sub-stoichiometric composition highlighted possible importance of hydrogen production due to oxidation, but did not quantify these effects. The KROTOS test with sub-stoichiometric composition allowed the quantification of hydrogen production thanks to post-test analyses and showed that the hydrogen production occurred during the premixing phase. For both tests, there is a limited fuel coolant interaction even being triggered.
- Experiments with rigid constraints (KROTOS) appear to produce lower calculated conversion efficiencies than those with less rigid constraints (TROI). Such differences, which appear to be counterintuitive, require further investigation.

- KROTOS and TROI results generally show consistent behaviour at two different geometric scales indicating the results may be extrapolated to reactor scale with appropriate uncertainty considerations.
- KROTOS and TROI experiments were instrumented with advanced instrumentation. These experiments produced both local and global data of interest, in particular, local void and melt distribution data for code assessment and improvement. The substantive amount of data generated in the experiments has not been fully explored yet. Also, no attempt has been made thus far to quantify the uncertainties in experimental data or calculated energetics.

The analytical programme was aimed at complementing the analytical work in WGAMA/SERENA activity, completed in 2006, by integrating the results of the experimental programme in the current phase, and by updating the capabilities of the FCI models/codes for use in reactor safety analysis. Important observations and conclusions from the analytical activities carried out in the OECD/SERENA project are:

- FCI codes improved, some more than others, during the course of the SERENA project. In general, the code predictions are in reasonable agreement with the data obtained in KROTOS and TROI experiments. However, the codes have not been assessed against the full spectrum of new experimental data. Analytical work should continue in this area.
- Melt solidification is recognised as a major contributor to the limitation of energetics for oxidic corium melts. There is a need to confirm the limiting effect of solidification for a wider range of materials, especially prototypical core material with large liquidus-solidus temperature interval. There is also a need to improve the solidification modelling with regard to its effect on suppressing fine fragmentation.
- Jet fragmentation, recognised as a key phenomenon, still needs improvements in modelling if uncertainties in energetics are deemed important for a specific safety application.
- Melt density as a material property is considered by some analysts to be a key parameter in explaining the material effect on explosion energetics. The high melt density of prototypic core melts yields smaller droplets, thus faster solidification and higher voiding. This may explain the lower energetics of the explosion with prototypic melts.
- The role of oxidation and the need for adequate modelling should be carefully examined for melts containing metal which may be more prototypic in reactor scenarios.
- Less effort has been put into specific modelling aspects of the explosion phase in the last several years. Work has been initiated recently on modelling of fine fragmentation.

The scope of the reactor application exercise was to verify whether progress made in the SERENA programme in understanding and modelling key FCI phenomena for reactor applications (mainly phenomena related to premixing, e.g., jet fragmentation, voiding, melt solidification, etc., as well as the role of melt properties) contributed to a reduction of scatter in code predictions for ex-vessel FCI, observed in the WGAMA/SERENA activity. A better consistency of the results was noted between various FCI codes although some discrepancies still exist on the absolute values. The scatter in most 2-D simulations is more due to the ultimate choice of the parameters (e.g., fragmentation criteria in the explosion phase) than to fundamental differences in the physics. This discrepancy will reduce further when the codes will have improved models based on the new experimental data produced in the project. Note the current experimental data have not been fully capitalised yet; accordingly, it will take some time to improve the models.

The OECD/SERENA project accomplished in large part its stated objectives. The project generated new experimental data for development of new phenomenological models closed to real reactor case conditions (corium composition), improvement of existing models, and assessment of FCI codes. The project also provided new insights; however, it would be sometime before the insights can be fully integrated into new and improved models and codes. It should be noted that the FCI models and codes can only be as precise as the experimental data and that there are inherent uncertainties in experimental data. While from a regulatory and risk perspective, a “fit-for-purpose” code may be adequate, a sustained modelling and code development strategy is encouraged to improve the knowledge base and increase confidence in using the codes.

SUMMARY AND CONCLUSIONS

(Prepared by Sud Basu-USNRC)

The SERENA Project Integration Report summarises the outcome of a broad range of activities conducted in the framework of the Nuclear Energy Agency (NEA) of Organisation for Economic Cooperation and Development (OECD) Steam Explosion Resolution for Nuclear Applications Project (OECD/SERENA), to address remaining issues on fuel-coolant interaction (FCI) mechanisms and their effect on ex-vessel steam explosion energetics. Briefly, the scope the OECD/SERENA project was to resolve uncertainties in the remaining issues by performing a limited number of well-designed tests with advanced instrumentation reflecting a large spectrum of ex-vessel melt compositions and conditions, and the required analytical work to bring the code capabilities to an adequate level for use in reactor safety applications. This scope was accomplished with the completion of three major tasks: (1) an experimental programme consisting of two sets of steam explosion experiments in two different facilities; (2) an analytical programme consisting of pre-test calculations in support of test specifications and post-test calculations in support of data analysis and code assessment, and a code benchmark exercise; and (3) a reactor calculation exercise repeating the one performed in the framework of the CSNI/WGAMA SERENA activity performed from 2001 to 2006 (also referred to as SERENA Phase I, published as CSNI/R(2007)/11).

The OECD/SERENA project was predicated upon the outcome of the WGAMA/SERENA activity (2001-2006), which indicated that voiding (gas content and distribution) in pre-mixture and also corium melt properties as well as uncertainties therein were the key issues to be resolved to reduce the scatter of the calculated steam explosion loads to an acceptable level. The WGAMA/SERENA activity concluded that while the scatter of the calculated in-vessel steam explosion loads is large, there is also a large safety margin between the upper bound of the calculated loads and the failure strength of the reactor pressure vessel. Thus, taking into account the uncertainties, an in-vessel steam explosion, in all probability, would not challenge the integrity of the vessel and hence the containment. On this basis, the in-vessel steam explosion issue was considered adequately resolved from a risk perspective. However, the large scatter in calculated ex-vessel steam explosion loads was such that in some cases, the calculated loads far exceeded the failure strength of the containment. The large scatter in steam explosion loads was attributed to a lack of precision in modelling jet breakup and voiding in pre-mixture, as well as the lack of a better understanding of the role of corium material properties.

Regarding the void content in a pre-mixture (a mixture of fragmented melt jet and surrounding coolant and voids) and its effect, only global void fraction data are available, which revealed to be insufficient to explain the explosivity of different melts. Regarding the material effect, particularly the fact that prototypic corium melts would produce rather mild explosions at best, considered opinion in the research community has been that the corium compositions used in past tests did not encompass sufficient variations to support conclusively the mildly explosive behaviour of prototypic melt. Thus, the OECD/SERENA project (sometimes referred to as SERENA Phase II programme) was formulated to resolve the uncertainties on the above issues by performing a limited number of well-designed tests with advanced instrumentation for measuring spatial distribution of voids, among other things, and using a spectrum of melt compositions and initial and boundary conditions which are representative of ex-vessel scenarios.

Experimental Programme

The objectives of the experimental programme were to provide data: (1) to clarify the explosion behaviour of prototypic corium melts and for validation of explosion models for prototypic materials; and (2) for steam explosion behaviour in two different geometries to verify the geometrical extrapolation capabilities of the codes. These objectives were to be accomplished by conducting complementary

experiments at two different facilities: KROTOS at the Commissariat l'Énergie Atomique et aux Énergies Alternatives (CEA) in Cadarache, France, and TROI at Korea Atomic Energy Research Institute (KAERI) in Daejeon, Korea. The proposed test matrix (see Table 1) is composed of two series of complementary tests: one in one-dimensional KROTOS configuration with about initially 5 kg of prototypical corium melt, and the other in multi-dimensional TROI configuration with about initially 20 kg of prototypical corium melt.

The KROTOS facility features one-dimensional behaviour of mixing and explosion propagation, and allows a clear characterisation of mixing (melt and void distribution), escalation, and propagation behaviour. TROI is more suited for testing the FCI behaviour in multi-dimensional geometry. The wider test section in TROI allows more prototypic sideways spreading of the mixing region (void and melt) and multi-dimensional pressure wave propagation.

Table 1. Experimental grid - KROTOS and TROI-SERENA Phase-2

n°	Objective	TROI	KROTOS
1	Challenging conditions <i>Mat 1: 70 wt%UO₂-30 wt %ZrO₂</i> Vessel: 0.4 MPa- 273K	TS-1 Melt superheating Thick jet	KS-1 Melt superheating Thin jet
2	Geometry effect <i>Mat 1: 70 wt%UO₂-30 wt%ZrO₂</i> Vessel: 0.2 MPa- 333K	TS-2 2 D Jet diameter: 50 mm	KS-2 1D Jet diameter: 30 mm
3	Reproducibility test-Idem test 2 <i>Mat 1: 70 wt%UO₂-30 wt%ZrO₂</i> Vessel: 0.2 MPa- 333K	TS-3 Idem test 2	KS-3 Idem test 2
4	Material effect: oxide composition <i>Mat 2: 80 wt%UO₂-20 wt %ZrO₂</i> Vessel: 0.2 MPa- 333K	TS-4 Melt superheating Thick jet	KS-4 Melt superheating Thin jet
5	Material effect: sub-oxide composition and oxidation <i>Mat 3: 70 wt%UO₂-15 wt%ZrO₂-15 wt%Zr</i> Vessel: 0.2 MPa- 333K	TS-5 Melt superheating Thick jet	KS-5 Melt superheating Thin jet
6	Material effect: oxide composition and large interval of solidification <i>Mat 4: 70 wt %UO₂-30 wt %ZrO₂ +Fe₂O₃+Low volatile Fission Products</i> Vessel: 0.2 MPa- 333K	TS-6 Melt superheating Thick jet	KS-6 Melt superheating Thin jet

Actual conditions used and/or achieved in SERENA tests as well as main results are provided in the table 2 (all values are rounded off to nearest decimal):

Table 2. Main results of experimental tests - KROTOS and TROI-SERENA Phase-2 (*: rapid instrumentation failed for KS-5)

Test ID	TS-1	TS-2	TS-3	TS-4	TS-5	TS-6	KS-1	KS-2	KS-3	KS-4	KS-5	KS-6
Delivered Melt Mass (kg)	15.4	12.5	15.9	14.3	17.9	9.3	2.4	3.9	0.8	2.3	1.7	1.7
Melt Temperature (K)	~3000	3063	3107	3011	2940	2910	2969	3049	2 850	2958	2864	2853
Melt Superheat (K)	145	228	272	171	140	239	109	189	-	38	64	182
Melt Composition (wt%) UO ₂ ZrO ₂ Zr U Fe ₂ O ₃ FP	73.4/26.6	68.0/32.0	71.0/29.0	81.0/19.0	76.0/18.3 5.0 0.7	73.3/18.5	70.0/30.0	70.0/30.0	70.0/30.0	80.0/20.0	80.1/11.4 8.5	73.0/20.4
Water Depth (m)	1.0	1.0	1.0	1.0	1.0	1.0	1.1	1.1	1.1	1.1	1.1	1.1
Water Temperature (K)	301	334	331	333	337	338	302	333	332	332	327	340
Sub-cooling (K)	115.9	61.7	65.1	64.0	57.7	56.9	118	60	-	62	67	54
System Pressure (MPa)	0.4	0.2	0.2	0.2	0.2	0.2	0.4	0.2		0.2	0.2	0.2
Fall Distance (m)	1.0	1.0	1.0	1.0	1.0	1.0	0.8	0.8	-	0.8	0.8	0.8
Jet Diameter (mm)	50	50	50	50	50	50	15	10	30	30	30	30
Triggering Time After Release (ms)	939	875	.875	1 040	1 046	1 050	931	922	-	851	1127	1542
Location of Melt Leading Edge at Trigger Time (m)	~0.3	~0.4	~0.4	~0.4	~0.1	~0.4	0.5	0.0	-	0.0	0.0	0.0
Void at Triggering (vol %)	~4	~3	~2	14-24	12-34	4-10	6.7	27	1	6	16	12
Max. Pressure (MPa)	17	10	12	20	7	25	34.7	23.3	-	44.7	-*	9.4
Impulse (N.s)	6640	>8000	~9000	>>9000	4680	>>9000	584	743	-	898	-*	~0
Steam Explosion	S/E	S/E	S/E	S/E	Steam Spike	S/E	S/E	S/E	-	S/E	Energetic event*	Located S/E
Conversion Ratio (%)	0.12	0.28	0.22	0.35	0.06	0.66	0.10	0.08	-	0.18	-	~0

It should be emphasised that at the time of preparing this report, it was possible to perform only a limited analysis of the huge amount of data. Based on a quick examination of the plethora of data produced in the two series of experiments, one might observe similarities of results between KROTOS and TROI experiments as well as noticeable differences. With that in mind, some of the more important observations are discussed below.

The steam explosion efficiency (expressed in terms of conversion ratio in the table above) in all tests is rather low, spanning a range between nominally 0.1% or less to no more than 0.7%, generally higher in TROI tests than in KROTOS tests. This observation may be somewhat counter-intuitive given that KROTOS tests are one-dimensional in nature and thus, are expected to yield higher efficiency relative to multi-dimensional TROI tests. The observation, however, is supported by the trend in void fraction evolution in TROI and KROTOS experiments. Specifically, KROTOS tests showed higher void fractions than the TROI tests. Note the void fractions were measured in the two facilities using different measurement techniques: in the KROTOS facility using an X-ray Linatron device and water level probe whereas in the TROI facility, using a differential pressure transducer system. There are also differences in the methods by which the conversion ratios were experimentally estimated in the two series of tests for the KROTOS and TROI facilities. These differences -and perhaps others- are likely to introduce uncertainties in the measured and computed values. Further analysis of test data accounting for uncertainties is highly recommended.

Another important observation from the experimental results relates to the steam explosion energetics of “eutectic” corium melt compositions, with thermo-physical and thermodynamic properties closed to pure compound. In previous TROI tests, 70 w/o UO_2 -30 w/o ZrO_2 melt composition (so-called “eutectic”) was found to be more explosive than 80 w/o UO_2 -20 w/o ZrO_2 melt composition (so-called “non-eutectic”), all the other experimental conditions except melt temperature being similar. So it was thought that the energetics of steam explosion was linked to the nature of the oxide corium melt, i.e., “eutectic” melt with little to no solidification interval produces higher energetics than “non-eutectic” melt with larger solidification interval. This finding could not be corroborated in the OECD/SERENA Project. In fact, an inverse behaviour for energetics was observed for experiments in both TROI and KROTOS facilities whereby 80 w/o UO_2 -20 w/o ZrO_2 melt composition produced somewhat higher energetics than 70 w/o UO_2 - 30 w/o ZrO_2 melt composition. Thus, it is concluded that the effect previously observed concerning the difference in explosion behaviour between oxide “eutectic” and oxide “non-eutectic” melt compositions seems no longer supported. This is further corroborated by analytical work, but the effect of solidification interval of corium melt on steam explosion needs further investigations.

Other important observations from KROTOS and TROI experiments in the framework of the OECD/SERENA project are:

- Prototypic core melt (i.e., predominantly a mixture of UO_2 and ZrO_2) does not produce strong explosion energetics relative to simulant melt compositions (i.e., KROTOS alumina tests) even though the calculated energetics in some TROI and KROTOS tests in the current series were higher than in the previous experiments with prototypic mixtures. The current series, in this regard, provide further confirmation of low steam explosion energetics of prototypic oxide corium melt.
- Some differences between TROI and KROTOS results are noted for melt compositions that are not fully oxidic (i.e., melt with sub-stoichiometric oxide corium compositions, test series 5). The TROI test with sub-stoichiometric composition highlighted possible importance of hydrogen production due to oxidation, but did not quantify these effects. The KROTOS test with sub-stoichiometric composition, on the other hand, was not as conclusive about the role of hydrogen,

even if post-test analyses have shown the highest production of H₂/kg of corium. The impact of the dynamic hydrogen production during fuel coolant interaction on:

- Another difference noted was with regard to conversion efficiency between the counterpart tests. Experiments with rigid constraints (KROTOS) appear to produce lower calculated conversion efficiencies than those with less rigid constraints (TROI). Such differences, which appear to be counterintuitive, require further investigation.
- KROTOS and TROI results generally show consistent behaviour at two different geometric scales indicating the results may be extrapolated to reactor scale with appropriate uncertainty considerations.
- KROTOS and TROI experiments were instrumented with advanced instrumentation. These experiments produced both local and global data of interest, in particular, local void and melt distribution data for code assessment and improvement. The substantive amount of data generated in the experiments has not been fully explored yet. Also, no attempt has been made thus far to quantify the uncertainties in experimental data or calculated energetics.

Analytical Programme

The analytical programme was aimed at complementing the analytical work in WGAMA/SERENA activity, completed in 2006, by integrating the results of the experimental programme in the current phase, and by updating the capabilities of the FCI models/codes for use in reactor safety analysis. The programme consisted of the following specific tasks:

- Perform pre-test calculations in support of test specifications, and post-test calculations in support of data analysis and code assessment;
- Organise a benchmark exercise with "blind pre-test" calculations for one test;
- Improve the understanding of those key phenomena that are believed to have major influence on the FCI process;
- Address the scaling effect and application to the reactor case;
- Give specific attention to the link between FCI models/codes and general system codes (e.g. COCOSYS) or integral codes (e.g. ASTEC, MELCOR); and
- Demonstrate the progress made in the OECD/SERENA project as compared with WGAMA/SERENA activity, by repeating the "ex-vessel reactor exercise."

The results of the first five tasks above are documented in a companion report which constitutes one of the main deliverables of the OECD/SERENA project namely, a report summarising the analytical activities. The report focuses on phenomenological understanding and modelling aspects and improvements therein, covering the phenomena of jet fragmentation, voiding, melt solidification, and explosion propagation, as informed by pre-test and post-test calculations. Emphasis is placed on improvement of phenomenological understanding based on new information generated either by the experimental part of the OECD/SERENA project or by other sources since the completion of the WGAMA/SERENA activity. Also, emphasis is placed on informing the FCI analytical tools and reaching a convergence in FCI modelling, to the extent feasible, thereby reducing the scatter in calculated steam explosion loads and increasing the confidence in code capabilities for reactor applications. The last task

and the results therein are documented in a second companion report which constitutes another main deliverable, i.e., the ex-vessel exercise synthesis report. This task and its results will be summarised in a separate section below.

The aim of the analytical activities was, among other things, to improve the common understanding of those key phenomena that are believed to have a major influence on the FCI process and steam explosion behaviour, and to investigate the scaling effect for the purpose of reactor applications. Emphasis was placed in particular on jet fragmentation, voiding, and corium properties as they relate to occurrence and propagation of steam explosion. In discussing the progress, emphasis was placed on improvement of phenomenological understanding based on new information generated either by the experimental part of the OECD/SERENA project or by other sources since the completion of the WGAMA/SERENA activity. Also, emphasis was placed on reaching a convergence in FCI modelling in various codes, to the extent feasible, and reducing the scatter in calculated steam explosion loads thereby increasing the confidence in code capabilities for reactor applications. The codes used in the present exercise were MC3D (developed by IRSN-CEA), JASMINE (developed by JNES), JEMI-IDEMO (developed by IKE), TEXAS-V (developed by UW) and TRACER-II (developed by KMU).

The jet fragmentation phenomenon is considered very important as it defines the initial and boundary conditions for subsequent processes involved in a steam explosion event, i.e., premixing, voiding, explosion triggering, and explosion propagation. There was considerable discussion during the WGAMA/SERENA activity regarding the difference in jet fragmentation behaviour being a key factor in the occurrence of stronger explosions in KROTOS alumina tests compared to those in KROTOS corium tests. The fragmentation processes are modelled in the existing FCI codes with a varying degree of fidelity. Experimental data from the OECD/SERENA project was used to make modelling improvement to some of the codes or to assess such improvement. A detailed discussion of fragmentation modelling improvements can be found in the companion report on analytical activities mentioned previously. It suffices to note that the jet fragmentation/breakup physics is viewed as a complex subject requiring considerably more investigation. For now, however, there appears to be a consensus towards a simplified approach based on some type of global fragmentation correlation.

Voids in a premixture provide a dissipative effect on triggering of an explosion and its propagation. Further, voiding is produced at the expense of coolant depletion which has an effect of reducing the energetic even if an explosion were to occur. These dual roles of voids in a premixture were recognised in past steam explosion studies. Most steam explosion experiments in the past, however, lacked advanced instrumentation to measure spatial distribution of voids. Only global void measurements were performed in these experiments. Thus, the analytical models in FCI codes relating to the influence of voids on explosion potential and energetics could only be assessed against global void measurements. The large scatter in ex-vessel steam explosion loads, calculated during the WGAMA/SERENA reactor exercise, was believed to have been the result, in part, of an insufficient knowledge of local voiding.

Conceptually, high voiding in a premixture is attributed to low energetics of any ensuing explosion and correspondingly, low voiding is attributed to high energetics. However, in theory, it is possible to have a low volume-averaged voiding in a premixture while the local void distribution in a smaller region of the fuel-coolant mixture may be high. This will, in effect, overestimate the explosion energetics and may explain why some FCI codes over predict steam explosion loads for prototypic materials.

In the context of analytical work within the OECD/SERENA project, only preliminary analysis of spatial void distribution could be made at present. In some evaluations, a non-homogenous flow is observed with large bulges of void flowing along the jet and thus, a quite sharp transition between highly voided and low voided regions. Such behaviour might facilitate the triggering of local explosions and it is important to assess this behaviour. More detailed post-test analysis are expected to provide data that can be

used to improve voiding models in the FCI codes which may result in more precision in the calculation results. Any future effort in this area should be tempered with the notion that a simplified fitness-for-purpose approach could be sufficient in contrast to a complex model with precise flow patterns and interface area transport. For now, though uncertainties remain regarding the precise influence of voiding in premixture, the preliminary analysis has not revealed anything that would contradict the conventional notion of the role of voiding in explosion energetics.

As the analytical work proceeded, it became evident that the phenomenon of melt solidification was one of the main limiting effects to strong explosions with corium because it reduces the amount of melt which may efficiently participate in the steam explosions process. Melt solidification during a non-energetic FCI process such as quenching is not new. However, its role in the energetic FCI process, i.e., steam explosion, has not been investigated at an appropriate level of detail in the past. This shortcoming was corrected in the current effort, leading to development of solidification models and their incorporation into some of the FCI codes. This is a significant finding of the OECD/SERENA project.

Melt solidification and its influence on the ability of melt droplets to undergo fine fragmentation are governed by a complex interaction of various processes which are not well understood and are difficult to model in detail. Therefore it is important to identify which processes have to be considered, and to establish which level of modelling would be sufficient for FCI codes with respect to reactor safety. For this purpose, the analytical activities focused on an investigation of melt droplet solidification, fragmentation of partly solidified melt droplets, and the influence of sub cooling. Further, the activities involved a thorough discussion of experimental observations and a review of the status of models and code capabilities.

During the premixing phase, the melt solidification process influences the droplets secondary breakup and the droplets agglomeration, and during the explosion phase it influences the fine fragmentation process. The most important is the inhibiting influence of the melt droplets solidification on the ability of the melt droplets to undergo fine fragmentation thereby contributing efficiently to steam explosion. Also, the effect of enhanced solidification in sub cooled conditions approximately compensates the effect of lower void build up. Thus, it is important to adequately model both the voiding effect and the solidification effect as the combined effect is likely to be more significant.

Partial solidification of the melt droplets during the premixing can produce solid crusts or layers with high viscosity resulting from mushy-type solidification of non-eutectic melts. This can prevent fine fragmentation during the explosion phase and thus, has an important effect in restricting the potential strength of steam explosions. The resistance of partly solidified drops against fragmentation depends on the conditions inside a pressure wave – the larger the relative flows, the larger the stresses that can lead to breaking of the crust.

The solidification process also depends on material properties, specifically, the material solidification characteristics. A eutectic melt will solidify at a given solidification temperature, whereas a non-eutectic melt will gradually solidify in a temperature range between the liquidus and solidus temperature. Thus, it is expected that the eutectic composition is more stable at under-cooled conditions than the non-eutectic one.

Melt density is another material property of importance with ramification to melt solidification, voiding, and jet fragmentation. While the difference in density between two prototypic melt mixtures (one eutectic and one non-eutectic as above) is negligible, the difference between a prototypic melt and a stimulant melt (e.g., alumina) is quite significant. This difference is believed to have a strong influence on voiding, melt mass in premixture, and melt solidification. Smaller drop sizes for the prototypic melt resulting from the higher density of corium compared to alumina lead to more void, and contributes to an enhanced solidification process. Also, the lower density of alumina results in lower melt settling velocity and hence, more melt mass in premixtures. The combined effect of melt mass, voiding, and melt

solidification can be quite significant which explains the difference in explosion energetic of the two melt types.

Other factors such as chemical interactions at the surface of melt drops, specifically, oxidation reaction with metallic component of the melt or oxidation of a sub-stoichiometric mixture, may be important to melt solidification and voiding processes, but these are generally considered as second order effects to explain the lower explosivity of prototypic melt compared to alumina. Modelling the influence of oxidation on melt solidification is very difficult and the uncertainties are large, especially if one considers that the chemical oxidation reaction significantly changes the melt material properties and influences the melt fragmentation process.

In summary, important observations and conclusions from the analytical activities carried out in the OECD/SERENA project are delineated below:

- FCI codes improved, some more than others, during the course of the SERENA project. In general, the code predictions are in reasonable agreement with the data obtained in KROTOS and TROI experiments. However, the codes have not been assessed against the full spectrum of new experimental data. Analytical work should continue in this area.
- Melt solidification is recognised as a major contributor to the limitation of energetics for oxidic corium melts. Attempts to incorporate the solidification effect in FCI codes led to important model improvements, e.g., modelling of crust formation and its impact on fine fragmentation, and modelling of drop size distributions to capture effect of different solidification times.
- There is a need to confirm the limiting effect of solidification for a wider range of materials, especially prototypical core material with large liquidus-solidus temperature interval. There is also a need to improve the solidification modelling with regard to its effect on suppressing fine fragmentation.
- Jet fragmentation, recognised as a key phenomenon that determines the amount of melt mass participating in explosion, still needs improvements in modelling if uncertainties in energetics are deemed important for a specific safety application.
- Melt density as a material property is considered by some analysts to be a key parameter in explaining the material effect on explosion energetics in previous KROTOS experiments. The high melt density of prototypic core melts yields smaller droplets, thus faster solidification and higher voiding. This may explain the lower energetics of the explosion with prototypic melts.
- Other effects related to chemical interactions could be present but are thought to be of secondary importance. Modelling of oxidation effects in codes is at an initial state of development and lacks experimental data for validation. The role of oxidation and the need for adequate modelling should be carefully examined for melts containing metal which may be more prototypic in reactor scenarios.
- Less effort has been put into specific modelling aspects of the explosion phase in the last several years. Work has been initiated recently on modelling of fine fragmentation.

Reactor Applications

The scope of the reactor application exercise was to verify whether progress made in the SERENA programme in understanding and modelling key FCI phenomena for reactor applications (mainly

phenomena related to premixing, e.g., jet fragmentation, voiding, melt solidification, etc., as well as the role of melt properties) contributed to a reduction of scatter in code predictions for ex-vessel FCI, observed in the WGAMA/SERENA activity. The codes used in the present exercise were MC3D (developed by IRSN-CEA), JASMINE (developed by JNES), JEMI-IDEMO (developed by IKE), TEXAS-V (developed by UW) and TRACER-II (developed by KMU).

The reactor exercise in the WGAMA/SERENA activity was performed with one axisymmetric PWR configuration. The present exercise includes one axisymmetric and one 3-D PWR configurations, and one axisymmetric BWR configuration. Base cases and sensitivity calculations were carried out, and multidimensional simulations were performed. Results were provided for selected premixing and explosion parameters, with the explosion pressures and impulses as the ultimate values for comparison.

A better consistency of the results was noted between various FCI codes although some discrepancies still exist on the absolute values. The scatter in most 2-D simulations is more due to the ultimate choice of the parameters (e.g., fragmentation criteria in the explosion phase) than to fundamental differences in the physics. This discrepancy will reduce further when the codes have improved models based on the new experimental data produced in the project.

Note that some codes have not been modified since WGAMA/SERENA activity (e.g., JASMINE) and other codes are still in the process of being improved on the basis of the experimental results produced in the OECD/SERENA project. The OECD/SERENA project experimental data have not been fully analysed yet; accordingly, it will take some time to improve the models. It is seen for instance that agreement on the criterion for stopping fragmentation in the explosion phase could noticeably reduce the scatter between the codes, e.g., MC3D and IDEMO (and possibly JASMINE, TRACER) predictions and TEXAS predictions, the latter by its modelling structure being inclined to produce more conservative loads.

Multidimensional reactor calculations using codes like MC3D and JEMI/IDEMO may provide additional information of interest in some situations (e.g., asymmetric melt pour). The necessity of such calculations should be examined further with regard to the impact on premixing flow configurations and explosion strength. Concurrently, the adequacy of one-dimensional calculations to conservatively bound the multidimensional effects should be examined.

In summary, important observations from the reactor application exercise are:

- A better consistency of the predictions of ex-vessel steam explosion was achieved among the various FCI codes used in the OECD/SERENA Project reactor synthesis exercise. The calculated loads are somewhat less than those reported in the WGAMA/SERENA reactor exercise, perhaps a consequence of different input and boundary conditions. Nevertheless, there is still a large scatter in calculated loads.
- The large scatter was attributed previously to an incomplete understanding of the effect of voiding. It is now believed that jet fragmentation plays a more important role, and that a more accurate modelling of fragmentation, using new data from KROTOS and TROI experiments, may help resolve the discrepancies between various code predictions. Melt solidification is another factor that may also play an important role in this respect.
- There is still an outstanding issue concerning FCI code predictions at the reactor scale, stemming primarily from the basis of extrapolating the experimental results to reactor scale. It is believed that while the voiding phenomena (in ex-vessel cases) may not play a significant role at the experimental scale, its importance at the reactor scale cannot be ruled out.

Concluding Remarks

The OECD/SERENA project accomplished in large part its stated objectives. The project generated new experimental data (in TROI and KROTOS facilities) for development of new phenomenological models, improvement of existing models, and assessment of FCI codes. TROI and KROTOS experiments provided further confirmation of low steam explosion energetics of prototypic melt even though the calculated energetics in some TROI and KROTOS tests in the current series were higher than in the previous experiments with prototypic mixtures. The project also provided new insights into FCI phenomena to improve the technical basis for regulatory decision making. However, it would be sometime before the insights can be fully integrated into new and improved models and codes.

Several new insights were also gained from the experiments including the significance of eutectic vs. non-eutectic melt composition, importance of oxidation and hydrogen production in melt containing metal, and the role of melt solidification in steam explosion energetics. The experiments also showed that melt superheat and coolant sub cooling have limited impact on steam explosion energetics.

The experiments produced both local and global data of interest, in particular, local void and melt distribution data for code assessment and improvement. The substantive amount of data generated in the experiments has not been fully explored yet. Also, no attempt has been made thus far to quantify the uncertainties in experimental data. This should be pursued as a follow-on activity. Particular attention should be paid to analysis of void fraction data in the respective test facilities, noting in particular the formation and dissolution of localised voiding evidenced in the radiosopic measurements in the KROTOS facility. Attention should also be paid to calculated conversion ratios in the respective facilities with particular focus on the consistency between the calculation methods.

A good deal of analytical work was done in the OECD/SERENA project and this work aimed to improve the FCI models and codes using the data generated in the experimental part of the project. Admittedly, the analytical work was not able to take advantage of the full set of experimental data as the last experiment was conducted only at the end of the project. Nevertheless, the work attempted to reach a convergence of understanding on the role of various FCI attributes (e.g., jet fragmentation, voiding, melt solidification, melt properties, etc.) in estimating steam explosion potential and energetics of prototypic reactor materials. The outcome of the analytical work did not reveal anything that would contradict the current understanding of the role of the above attributes in steam explosion energetics.

In general, FCI codes have improved and code predictions are in reasonable agreement with the data obtained in KROTOS and TROI experiments. Better consistency was achieved among the various FCI codes in the prediction of ex-vessel steam explosion, and the calculated loads were somewhat less than those previously reported though there remains still a large scatter in the prediction of ex-vessel steam explosion loads. In that sense, the project did not provide a definitive resolution of the ex-vessel steam explosion issue.

Notwithstanding the progress made in the SERENA project, certain aspects of FCI and steam explosion research would continue to require further attention. The analytical work thus far confirms that a good understanding of the jet fragmentation process is key to developing robust FCI models which can fully explain the difference in steam explosion behaviour of different melts. The jet fragmentation/breakup physics is admittedly a complex subject requiring considerably more investigation to assure high fidelity modelling. However, for practical application of FCI codes and considering risk perspective, there appears to be a consensus towards a simplified approach based on consideration of some type of global fragmentation correlation.

The FCI codes have not been assessed against the full spectrum of new experimental data. Analytical work should continue in this area as it is believed that the new experimental data will be useful in improving further the FCI models and codes, which may help resolve the discrepancies between various code predictions. There are also other issues such as scalability of small-scale experimental results to reactor applications, development of new phenomenological models, and further improvement and assessment of multidimensional FCI codes. Particular attention should be paid to melt solidification modelling. Also, modelling of the pressurisation process at high pressures needs further improvement.

Finally, it should be noted that the FCI models and codes can only be as precise as the experimental data supports and there are inherent uncertainties in experimental data. While from a regulatory and risk perspective, a “fit-for-purpose” code may be adequate, a sustained modelling and code development strategy is encouraged to improve the knowledge base and increase confidence in using the codes.